
**STUDY OF OPTICAL
TECHNIQUES FOR THE AMES
UNITARY WIND TUNNELS
PART 2. LIGHT SHEET AND
VAPOR SCREEN**

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PART 2. LIGHT SHEET AND VAPOR SCREEN

Summary

Light sheet and vapor screen methods have been studied with particular emphasis on those systems that have been used in large transonic and supersonic wind tunnels. The various fluids and solids used as tracers or light scatters and the methods for tracer generation have been studied. Light sources from high intensity lamps and various lasers have been surveyed. Light sheet generation and projection methods were considered. Detectors and location of detectors were briefly studied. A vapor screen system and a technique for location injection of tracers for the NASA Ames 9 x 7 Supersonic Wind Tunnel were proposed.

Introduction

There are many aerodynamic and fluid mechanics problems that contain highly complex three-dimensional flow fields. An example is the modern high performance fighters that use swept wings, leading-edge extensions and strakes to generate vortical flows over the control surfaces. These vortices along with vortices from the nose of the aircraft create a highly complex three-dimensional flow field. To evaluate the influence of the wing, strakes and leading-edge geometries on the aircraft's performance, the complex vortical flow field needs to be visualized. Ordinarily optical methods like schlieren and shadowgraph are not amiable to complex three-dimensional flows because the planes within the flow are obscured by those closer to the viewer. One technique that partially overcomes this difficulty is "light sheet" visualization¹⁻³, with tracers dispersed uniformly in the flow, a thin intense sheet of light cutting through the flow will illuminate the tracers to indicate the flow in that plane. By viewing different planes, a composite picture can be obtained.

For many years, the NASA Ames wind tunnels have used light sheets for flow visualization. In fact, Allen and Perkins⁴ introduced the concept of "vapor screen" which utilized water vapor as the tracer. The existing Ames 6 x 6 Foot Supersonic Wind Tunnel schlieren arc lamp and mirror was used to generate the light sheet. Their experiment was to study vortices from slender bodies. According to Allen and Perkins, the "vapor screen" made the vortices much more visible. Over the years the laser has been incorporated to make the system called the "laser vapor screen." Currently the NASA Ames 11 x 11 Foot Transonic Wind Tunnel is constructing a new system based on a new compact high efficiency infrared diode laser. Included is a traverse mechanism that can project the light sheet throughout the test section. There is also a need for laser vapor screen systems in the other tunnels such as the 9 x 7 Supersonic Wind Tunnel. Therefore, the purpose of this study is to survey, review, and to

evaluate possible systems for these facilities. Particular attention will be given to those systems that have been operated successfully in larger wind tunnels and on components that can be purchased commercially. This study will look at the various components of a light sheet system: 1. tracers, 2. light source, 3. light sheet generator, and 4. recorders.

Tracers

The injection of a foreign material into a fluid to create a trace of the flow is an old and proven technique. Color dyes, fluorescent fluids, hydrogen bubbles, metal and plastic particles, and even milk have been used in water tunnels.^{5,6} Balloons⁷, smoke flares, and natural condensation⁸ have been used in flight. Smoke, helium filled soap bubbles and chemicals have been highly developed for low speeds.^{5,9,10} Since this study is for high speed wind tunnels, the above tracers will not be discussed. Particles such as water vapor, ice, and a number of chemicals for use at high speeds will now be discussed.

1. Water.

Water is the most common tracer material used in high speed wind tunnels. It is non-toxic. By adding water to the air stream, the relative humidity is raised and as the air expands through the nozzle, condensation occurs. At subsonic and transonic speeds, the water condenses to water vapor. At supersonic speeds, ice particles are formed. McGregor¹¹ gives a comprehensive account of the condensation process. The mechanism of condensation on dust nuclei at low supersonic speeds and the spontaneously generated nuclei at higher supersonic speeds was discussed. The effect of the dew point was investigated. More recently Snow and Morris¹² studied water condensation for large scale wind tunnels and extended the analysis to lower Mach numbers. A dew-point controlled feedback system to inject water into the tunnel coupled with an empirically determined operating curve was devised. Tests to measure the size distribution of the water particles were made.

McGregor also explained the vapor screen picture at shockwaves, expansion waves, and vortices on the principles of compression heating and inertia effects. Since the vapor screen method has been widely used to study vortices, the vapor screen formation of vortices will be repeated.

At supersonic speeds, the radial acceleration of the vortex produces a powerful centrifuging action which spins the water or ice particles from the center of the vortex. The center having a lack of light scattering particles will appear dark in the vapor screen. At subsonic speeds, the vapor screen picture for a vortex shows an "image reversal." The vortex center appears white on a darkened background. It is believed that the higher velocities inside the vortex core causes a sufficient temperature drop to cause condensation to occur at a greater rate than centrifugal forces could sweep the water particles for the vortex core. Bright vortex images have been seen to Mach numbers of 0.4 and 0.6 by Erickson.^{13,14} Dark vortex images have been reported by Morris¹⁵ at Mach numbers of 2.86 and 4.5.

The vapor screen technique with water will become less efficient and cease to work at sufficiently low Mach numbers due to insufficient temperature drops to cause condensation. At the higher supersonic and hypersonic speeds, the water vapor screen should work, in principle. W. Lockman and K. Owens tried a different scheme at Mach number 7 in the NASA Ames 3.5 Hypersonic Tunnel. Instead of injecting water which may be impractical to do in a heated blow-down tunnel, they lowered the stagnation temperature to around 1100°F. This caused static temperatures to drop to the liquefaction temperature of oxygen. The oxygen particles became the tracers and images could be seen.

The disadvantage of using water is due to condensation which releases heat to the flow with changes in static conditions and Mach numbers. This problem of "condensation shocks" in nozzles has been studied by Oswatitch¹⁶. McGregor studied the effects of humidity and found that static pressures can change by 5% to 20% at Mach numbers of 1.51 and 1.81 as humidity was increased. Recent data¹⁵ from NASA Langley Unitary Plan Wind Tunnel at Mach number of 2.0 show that the stagnation pressure was reduced by 5%, Mach number by 0.05 and static pressure by 4%. Typical normal-force coefficients differ by about 5% from dry air data. Therefore, valid forces and moments cannot be acquired during vapor-screen runs. However, it is felt that the interpretation of the vapor-screen photographs are not compromised.

Local condensation has been noticed by McGregor in the R.A.E. Bedford 3 Foot Tunnel and also by Snow and Morris in the NASA Langley Unitary Plan Wind Tunnel. This was attributed to supersaturation conditions. This problem has not been noticed at NASA Ames 6 x 6 Foot or 11 x 11 Foot Tunnels nor at the David Taylor Research Center 7 x 10 Foot Transonic Tunnel.

2. Carbon tetrachloride, CCl₄.

To overcome the condensation shock problem, McGregor searched for material that has a lower latent heat of vaporization. CCl₄ has nearly ten times less heat of vaporization than water. It was used for a test at Mach number = 2 and it did reduce the situation. However, it is known that CCl₄ is toxic and carcinogenic.

3. Dioctyle phthalate, DOP

Griffen and Votaw¹⁷ proposed using DOP for flow visualization. DOP is non-toxic, non-corrosive, has a high flash point and chemical inertness. The particles can be easily generated at room temperature in an atomizer that uses compressed air. The particles are of a known size, less than 1.3 microns. The aerosol can be fed into the wind tunnel through a tube. Snow and Morris¹² tried DOP in the NASA Langley Unitary Plan Wind Tunnel. The commercial generators were simple to use and inexpensive. The unit supplied particles of 0.8 microns in diameter at rates up to 10¹¹ to 10¹² particles per minute. But it could not fill a large tunnel of the order of 7080 cubic meters. However, used as

a "smoke wane" or injected through an orifice in the model, it could be used to tracked a streamline or define a vortex.

4. Propylene glycol.

Another non-toxic, non-carcinogenic, and one that does not contaminate or damage the tunnel is propylene glycol. Bruce, Hess, and Rivera¹⁸ developed a vapor generator for this fluid. The vapor is injected into the air stream and condenses to form particles. As in the case for water, it can condense on dust nuclei in the air or by spontaneous nucleation depending whether the temperature and pressure are above or below the supersaturation curve. Spontaneous nucleation creates much more particles, so it was used. The vapor generator provided satisfactory seeding from low subsonic to transonic speeds for pressures of 1 atmosphere down to 0.1 atmosphere. The seeder was used for a laser light sheet to study vortices from a semi-span clipped delta wing.

5. Titanium Tetrachloride - $TiCl_4$.

This chemical is a liquid and reacts with moist air to produce a dense white fume. It is very easy to use; typically a small amount is dap on the model or injected from the model. However, the by-products of the reaction are titanium dioxide and hydrochloric acid which is very corrosive and toxic. In special situations, it could be used. For example, Rivir and Rolquemore¹⁹ used it to study turbine film cooling and bluff-body combustion flames.

6. Smoke.

Smoke used in low speed smoke tunnels give unrivaled flow visualization pictures. Snow and Morris experimented with various ways to make smoke for large high speed wind tunnels. The effort was not successful. Note that smoke has been used on specially designed "smoke tunnels" at high speeds.

7. Other particles.

Polystyrene latex spheres, silicone oil, rare earths are some of the material used as tracers for LDV applications. Some of these could be easily used for light sheet visualization. These materials are non-toxic and can be easily generated in small quantities. Therefore, this application would be limited to local injection to visualize a small portion of the flow field.

Table I. is a summary of some aerosols used for light sheets.

Light Source

Many different types of light sources have been used. These include high power mercury, xenon flashlamps and all types of lasers. The power of the lamps are very high, the order of kilowatts. Because the laser beam is

collimated and intense, the order of watts is sufficient. However, to produce a good light sheet, the light must be: 1. sufficiently intense so that the scattered light provide good contrast and spatial resolution of the flow field; 2. the light sheet has a very narrow width with minimum variation in width across the test section; 3. the sheet is sharp-edged so that a minimum of stray light enters the wind tunnel. The intensity needed will also depend on the size of the particles, the wavelength of the light, the recording medium, and the angle of view of the image. Most light sources being used are in the visible wavelengths. The near infrared wavelengths are coming into use.

1. Mercury capillary lamps.

Mercury arc-lamps are an old and proven technology that is familiar to the aerodynamic community. The lamps have been used for many decades for schlieren. In fact that first vapor screen system used a mercury arc-lamp. The power of these lamps can range from hundreds to thousands of watts. They can be operated in both continuous wave or pulse modes. The high radiant output power is due to the high pressure operation which is typically around 100 atmospheres. Typical lamp efficiencies are 2 to 3 percent which translates into the order of 100 watts output for a 4 kw lamp. To increase the output ellipsoidal mirror collectors and fresnel lens have been tried.¹² It was shown that improvements of 8 times can be obtained with a commercial mirror. But there were aberration problems, noise from air cooling, and heating problems that still require a solution.

2. Flash lamps.

Flash lamps can provide an intense periodic light source. Xenon lamps operated at energy levels of up to 100 Joules and can be pulsed between 1 to 60 Hertz or even higher. Saber, et al.²⁰ used a flash lamp to study unsteady flows. A 30 Joule flash lamp with a 1% conversion efficiency to produce 30 kw pulses having 300 nanoseconds. A computer aid design optics package was used to design the lens and filters to produce a pencil of light which can be expanded into the light sheet. Although it seems complicated, the authors cite the low cost compared with a pulsed laser of the same power.

3. Argon-ion laser

This is the most common laser being used for generating light sheets. It has been used in most of the laboratories and research centers in the U.S. and abroad^{2,14,15,21,22}. This laser has continuous wave output, good stability and beam quality. The lifetime is about 2000 hours of operation before requiring replacement of the tube. The laser is usually several feet long and if space is small, fiber optics may be needed to transmit the beam to the test section. Water cooling is normally required and 220 or 440 volts (sometimes 3 phase) is needed. The radiant output is in the visible wavelengths with the blue and green lines giving over 80% of the energy. For light sheets, this is of no concern and only the total energy is considered. The typical power used is around 3 to 6 watts although power as high as 18 watts have been tried. The

cost of argon-ion lasers goes from \$10,000 to \$30,000. The NASA Langley Unitary Plan Wind Tunnel²² state of the art light sheet system uses a 5 watt argon-ion laser.

4. Helium-Neon laser

Helium-neon lasers have been used for vapor screens^{15,23}. Morris¹⁵ compared a mercury lamp, 4 watt argon-ion and 15 mw helium-neon in the Langley Unitary Plan Wind Tunnel. The helium neon provided high quality vapor screen photographs of vortices at Mach number of 2.86. The helium-neon photographs compared very well with those using the higher power argon-ion laser. Conversation with Joe O'Hare of AEDC reveals routine use of helium neon lasers for vapor screen work. They have developed small units with telescope cylindrical lens that provides an adjustable fan light sheet. These lasers are also being used at the Langley BART Tunnel and at AEDC in scanning systems in which the laser beam is oscillated rapidly by a mirror to form the light sheet.

The helium-neon lasers are gas lasers with low power outputs, typically from 1 mw to 75 mw. They give a continuous wave use of light in the red, the main wavelength being 632.8 nm. They are small, usually about the size of a flashlight. The power supply is small and uses 110 volt A.C. No cooling is necessary. They are very robust and unlike the argon-ion lasers, do not have to be turned on periodically to prevent tube contamination. Its operational lifetime of up to 100,000 hours is quite long. Cost is inexpensive, about \$1300 for a 10 mw and about \$7000 for a 35 mw laser.

5. Neodymium YAG:Nd:YAG laser

The ND:YAG solid state laser has been used primarily for light sheet visualization of unsteady flows. Rivir and Roquemore¹⁹ used it for turbine blade film cooling and bluff-body combustion flows. Veret²⁴ used it for vortex structures and vortex breakdown. Both Rivir and Veret used a frequency doubler to operate in the green. This reduced the laser energy by about 30%. The Nd:YAG normally operates at the near infrared wavelength of 1064 nm. Note that CCD cameras do record at the near infrared, but at lower efficiencies. These lasers typically have outputs of 0.01 to 150 Joules at the near infrared. The frequencies can go up to the KHz range. The pulse width of each pulse is typically in the tens of nanoseconds. The output beam can be donut shaped in the near field, but with a spatial filter change to a TEM₀₀ mode with gaussian energy distribution in the far field with a beam diameter of 1 to 2 mm. Prices can range from \$50,000 to \$120,000. The flashlamps that pump the Nd:YAG rod usually last about 200 hours.

6. Ruby laser

The ruby laser was used by Soreide, et al.²⁵ for a pulsed laser light sheet visualization of the vortex of a rotating rotor blade. The laser provided 2 Joules of energy in a 30 ns pulse. The output beam was 3/8" diameter. A pair

of simple plano-convex lenses produced a sheet of 0.05" ten feet away. Stanislas²⁶ used a ruby laser of 60 mJ of 15 to 20 ns duration to study several types of flows: a flat plate and air intake at high angle of attack and unsteady wall boundary layers. The laser was operated at single pulse. The tracer used was smoke. The ruby laser can cost between \$15,000 to \$70,000. They are pumped by flashlamps which probably have similar lifetime of 10^6 shots or 200 hours as those for a Nd:YAG.

7. Copper Vapor laser.

The copper vapor laser was used by Wlezien²⁷ for quantitative visualization of acoustically excited jets. The light sheet was formed by a cylindrical lens and a parabolic mirror was used to align the light sheet through the jet axis. The laser typically flashes at a repetition rate of 6 K Hz with a pulse duration of about 10 ns. The pulses were synchronized with the lowest subharmonic frequency of the excited jet at 400 Hz to produce phase-averaged images of the flow. A RCA Ultricon low-light-level camera was used and it recorded images when the flow was not visible to the eye.

Copper vapor lasers operate at the green and yellow lines and have efficiencies of 0.5 to 1.0%. Typical pulse rates are between 6 to 20 k Hz. It can be triggered and average power is 10 to 40 watts with pulse energy from 2 to 10 mJ. Peak power can reach 0.5 megawatt. Costs are \$50,000 and higher. The gas tube life is about 2000 hours and the gas must be replaced every 300 hours.

8. Diode laser.

Weber, Schreiner, and Gilbaugh²⁸ are developing a diode laser light sheet for the NASA Ames 11 x 11 Foot Transonic Wind Tunnel. Recently, this new system was compared to an argon-ion system in the NASA Langley 7 x 10 Foot High Speed Wind Tunnel at a Mach number of 0.4. A fighter model was tested from 20 to 50 degrees and the vortices were visualized by both systems. The argon-ion laser was operated at 0.25 watts and the diode laser was operated at 8 watts. A spatial filter was required for the diode laser to get a clean light sheet. This reduced its effective power to 2 to 3 watts. The diode laser operates at about 800 nm (near infrared). CCD cameras have peak sensitivity at these wavelengths which matches the laser. Special optics were needed to convert the non-circular shape and large divergence beam, $10^\circ \times 35^\circ$ before it could be used for a light sheet. The longer wavelengths could be a problem if the particles of water which scatter the light gets smaller than 1 micron. The lighter scattered depends on $(d/w)^n$, where d is particle diameter, w is the laser wavelength and n can be as large as 6. For small particles, scattering efficiency could drop by 94% according to the authors. This would negate the advantages of the diode.

Comparison of the two systems shows that both systems work well at model angle of attacks between 20° to 40° . At 44° , the light sheet image was

very dim, but the agron-ion was still good. At 480, the light reflected from the model was strong enough to smear the image. The advantages of the diode laser are extremely small size, good conversion energy of nearly 40%, and is robust. For the 11 x 11 Foot application, the small size is important due to lack of space and the long test section that needs to be covered. The diode laser is made of GaA/As and costs about \$10,000. Typical lifetime is about 10,000 hours.

The laser diode light sheet generator can be designed into a small package. For example, the one being designed for the NASA Ames 11 x 11 Foot Transonic Wind Tunnel, figure 1a, is about 2" x 4". Figure 1b shows the diode light sheet projector mounted on a remotely controlled angular table. Figure 1c is a sketch of how the light sheet projector will be deployed in the wind tunnel. The dark black bars in the top and corner of the wind tunnel are the location of the traverse systems that allow the light sheet projector to cover the entire length of the test section. Cost of the projector and traverse and windows is about \$90,000.

Light sheet generation and Projection

1. Lenses.

Most light sheet generators¹¹⁻¹⁵ use one or more lenses to form the light sheet. With a laser that has a highly collimated beam, (most laser beams have about 1 milliradian divergence) a single lens or even a glass rod will decollimate the beam in one direction to form a thin light sheet, figure 2a. Snow and Morris recommends using a plano-rod, figure 2b to reduce reflection losses. They also showed a telescope arrangement of two lenses to vary the angle of the light sheet, figure 2c. Hentschel and Stoffreg²⁹ proposed a three lens arrangement to change the size of the sheet, figure 2d. Other lasers like the Nd:YAG which have a non-gaussian beam, or a laser diode which have non-symmetric and widely diverging beams require more elaborate conditioning before it can be formed into a light sheet. Arc-lamps and flash-lamps also fall into the category of beam pre-conditioning. Snow and Morris as shown in figure 3 used an adjustable knife-edge filter and cylindrical lenses to form the light sheet. It might be mentioned that arc-lamps require cooling which could cause distortions in the light sheet.

2. Scanning.

Scanning or sweeping the laser beam are being used at a number of facilities. The advantage is that there is no optical degradation of the high-quality laser beam. The size and location of the light sheet can be easily adjusted. With a program, predetermined positions of the light sheet pattern can be easily done. Snow and Morris¹² developed a rocking mirror driven with an eccentric cam for sweeping the beam. Prenel, Porcar, and Diemunsch³⁰ used two oscillating mirrors mounted on galvanometers, figure 7. General Scanning³¹ makes galvanometer systems for lasers. Both system modules or

custom systems can be purchased. A vision kit that includes an X-Y scan head, drive electronics, lens and optical rail would cost around \$2200. Figure 8 is a picture of a system.

3. Projection.

Projection of the light sheet into the test section is highly dependent on optical access and space to put the light sheet generator. For wind tunnels that have large windows on the sides of test section, a simple solution is to place the light sheet generator near the window and project the beam into the tunnel, figure 4. To cover the test section, a traverse system is normally added. The new NASA Ames 11 x 11 Foot uses a compact rail-flexible chain traverse system. Figure 5 shows a projection system by McGregor that is based on using the optical components of the schlieren system. Another configuration keeps the laser fixed with the beam and the lenses moved on traverse systems. The advantage is that the mirrors and lenses can be easily moved, figure 6. Fiber optics have also been used for transmitting the beam from the laser to the light sheet generator. This type of system can be used where optical access and space is critical or the tunnel environment requires the laser to be put some distance away.

Recorders

1. Cameras and video.

The 70 mm cameras have been used by many to record the vapor screen images. According to Snow and Morris, a medium resolution film can resolve 60 lines per millimeter, or $60 \times 70 = 4200$ lines around the image field. In terms of television, there are 8400 lines because the black line and the adjacent white space are each counted as a line. Some disadvantages with cameras is that they are large and put in a protective housing for use inside the tunnel could encroach on choking the tunnel. The camera, if it is located inside the tunnel, is inaccessible during a run in case of malfunction. Finally the turn-around-time for film processing must be considered.

The video camera is also being used. There are miniature cameras that can easily be located on the model sting. The video cameras have resolutions of 400 to 800 lines so it is not as good as film. On the other hand, the eye can pick up and distinguish motion from the video. The video also allows image processing to be performed for enhancement of the image. The video also allows the monitoring of the data in real time. Low light videos allow these devices to operate where film cameras may have problems.

2. Location of camera and video

The location of the detector depends on what is to be visualized. Shock waves, boundary layer separation and reattachment, wakes, jets and vortices have been visualized by the light sheet method. Obviously, the detector must be placed so that the view is at some angle to the plane of the light sheet. For most cases, the best view is normal to the light sheet. However, the 90° view

may not be the one for the "best image" since the light being scattered by the tracers is the minimum at this angle, especially for the small scattering particles. Figure 9 shows some of the normal viewing locations used in wind tunnels: 1. detector behind the model; 2. detector on same side of light source (back scatter); 3. detector on opposite side (forward scatter). The forward scatter direction usually gives the most light. Flare or light scattered or reflected from the model also influences the location of the detectors.

Light sheet system: NASA Ames 9 x 7 Supersonic Wind Tunnel.

Laser vapor screen flow visualization is being used by many supersonic wind tunnels to study complex flow fields missiles at high angles of attack, delta and slender wings at high angles, highly maneuverable fighters, and supersonic transports. Vortices, separation, shocks, and wakes are some of the typical parameters being studied. Currently the 9 x 7 tunnel has no laser vapor screen capability although vapor screen tests have been previously used. A laser vapor screen system would be a valuable diagnostic tool and will be complimentary to the schlieren which is being modernized.

The 9 x 7 tunnel has a Mach number range of 1.55 to 2.60. Its test section is 7 feet high by 9 feet wide with 2 sets of 28" diameter windows mounted in rotatable 48" steel frames, figure 10. The model pitches in the horizontal plane, i.e. toward the windows. The usual view of a wing-body model is the top or bottom as opposed to the side view in most wind tunnels. The distance from the source of the light sheet to the model would be about 4.5 feet. A model with a wing span of 4 feet would require a light sheet fan angle of about 50°. This would set the requirements for the light sheet and laser power.

The fluid to be used as the tracer particle should be water. Water is non-toxic and occurs naturally in the air used in this tunnel. Normally, the air must be dried before using it in the tunnel. It would be easy to set the dew point at around 0° F to 10° F for the vapor screen conditions. Other attractive tracers would be DOP and propylene glycol which are non-toxic and could be generated in known sizes and amounts. Consider an experiment to track streamlines in a wing vortex for CFD radiation. A small of these particles can be ejected from an appropriate orifice in the model and tracked to defined streamlines.

The light source should be a laser. Based on many studies, it can be concluded that highly collimated laser beams make the best light sources for light sheets. The first choice would be to use an existing 35 mw HeNe laser. There is a good possibility that there is sufficient intensity based on NASA Langley's use of a 15 mw HeNe in their Unitary Plan Wind Tunnel which is 4 x 4 feet.

The light sheet could be formed with a straight-line generating lens costing about \$185. Set-up time should be a day or two. A low flux black and white video camera should be used since the light scattered should be low. The optimum video camera location will be determined by experimentation.

The other choices for a light source would be the laser diode being developed for the 11 x 11 Foot Transonic Wind Tunnel. There is the unresolved issue of insufficient scattered light because of the infrared wavelength. In any case, this laser should be tried in the 9 x 7. Note that laser diodes with visible wavelengths are coming on the market that have power in the several watt range. The final choice would be an argon-ion laser having powers of 1 to 4 watts. The division has a couple of argon-ion laser and other branches at Ames probably could loan one for evaluation purposes.

Recommendations

Laser vapor screen systems should be provided for the current and future needs of the 9 x 7 and 8 x 7 Foot Supersonic Wind Tunnels. A low power laser vapor screen system using a 35 mw HeNe laser and a simple line generator should be breadboarded for the 9 x 7 tunnel to determine if it has sufficient light.

Higher power vapor screen systems should be developed for the 9 x 7 tunnel if the low power system is not adequate.

The technique of local injection of non-toxic DOP or propylene glycol should be developed for visualization of streamlines. For example it could be used to validate CFD calculations of streamlines in a vortex.

The schlieren should be used along with the laser vapor screen whenever feasible. The techniques provide complementary data since they usually look at the flow at widely different angles.

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TABLE I.

Aerosals for Flow Visualization

| Aerosal | Generation | Safety | Comment |
|---------------------------|--------------|------------|-------------------------------------|
| Water | Condensation | Non-toxic | easy to generate |
| Carbon Tetrachloride | Condensation | Toxic | easy to generate |
| Tetrachlorethylene | " | " | " |
| Tetrachloroethane | " | " | " |
| Pentachloroethane | " | " | " |
| Diocetyl phthalate | Atomizer | Non-Toxic | easy to generate |
| Propylene glycol | Atomizer | Non-Toxic | easy to generate |
| Smoke, Kerosene | Atomizer | Semi-Toxic | require low turbulence tunnels |
| Mineral Oil | Atomizer | Non-Toxic | small quantity generated |
| Polystyrene latex spheres | Atomizer | Non-Toxic | know size, small quantity generated |
| Titanium tetrachloride | Chemical | Toxic | easy to generate |

TABLE II.

LIGHT SOURCES FOR LIGHT SHEETS

| Light Source | Power | Safety | Comment |
|----------------------------|----------------|---------------|--|
| Arc-lamps, Flash-lamps | 0(100 watts) | Non-hazardous | Need conditioning to obtain good light sheet. |
| Argon-ion laser | 1-20 watts | Hazardous | Expensive, requires maintenance. |
| Helium-Neon laser | 1-70 mw | Hazardous | Long life, no maintenance |
| Nd:YAG laser Ruby laser | .01-150 Joules | Hazardous | Expensive, used for unsteady flows, requires maintenance. |
| Copper vapor laser | 10-40 watts | Hazardous | Expensive, requires maintenance, unsteady flow applications. |
| Diode lasers | 0.1-10 watts | Hazardous | Need conditioning to obtain good light sheet. |

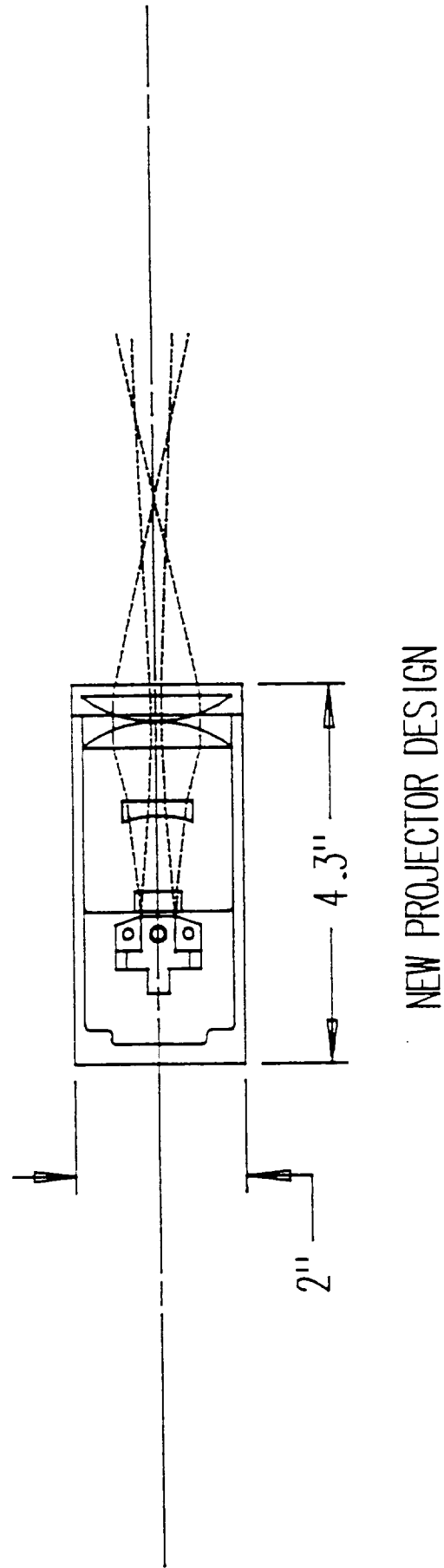
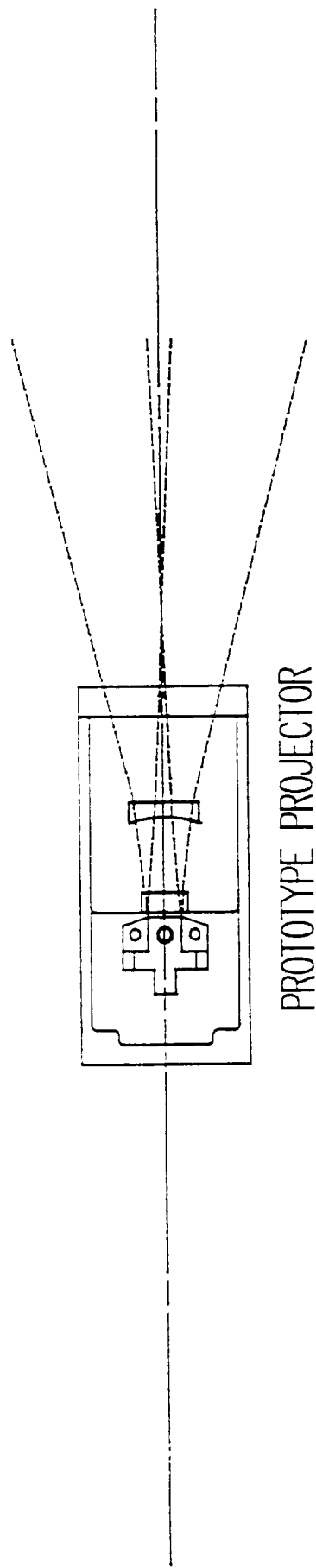


Figure 1a. Laser diode light sheet generator for the 11x11 Transonic Wind Tunnel. (after B. Weber)

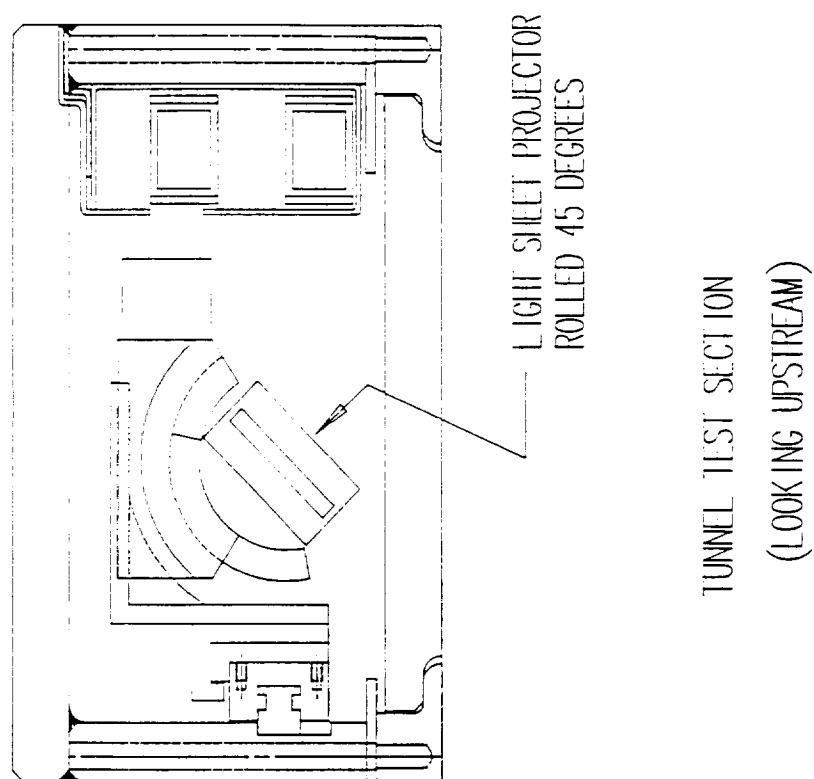


Figure 1b. Cross section view of generator and traverse system.

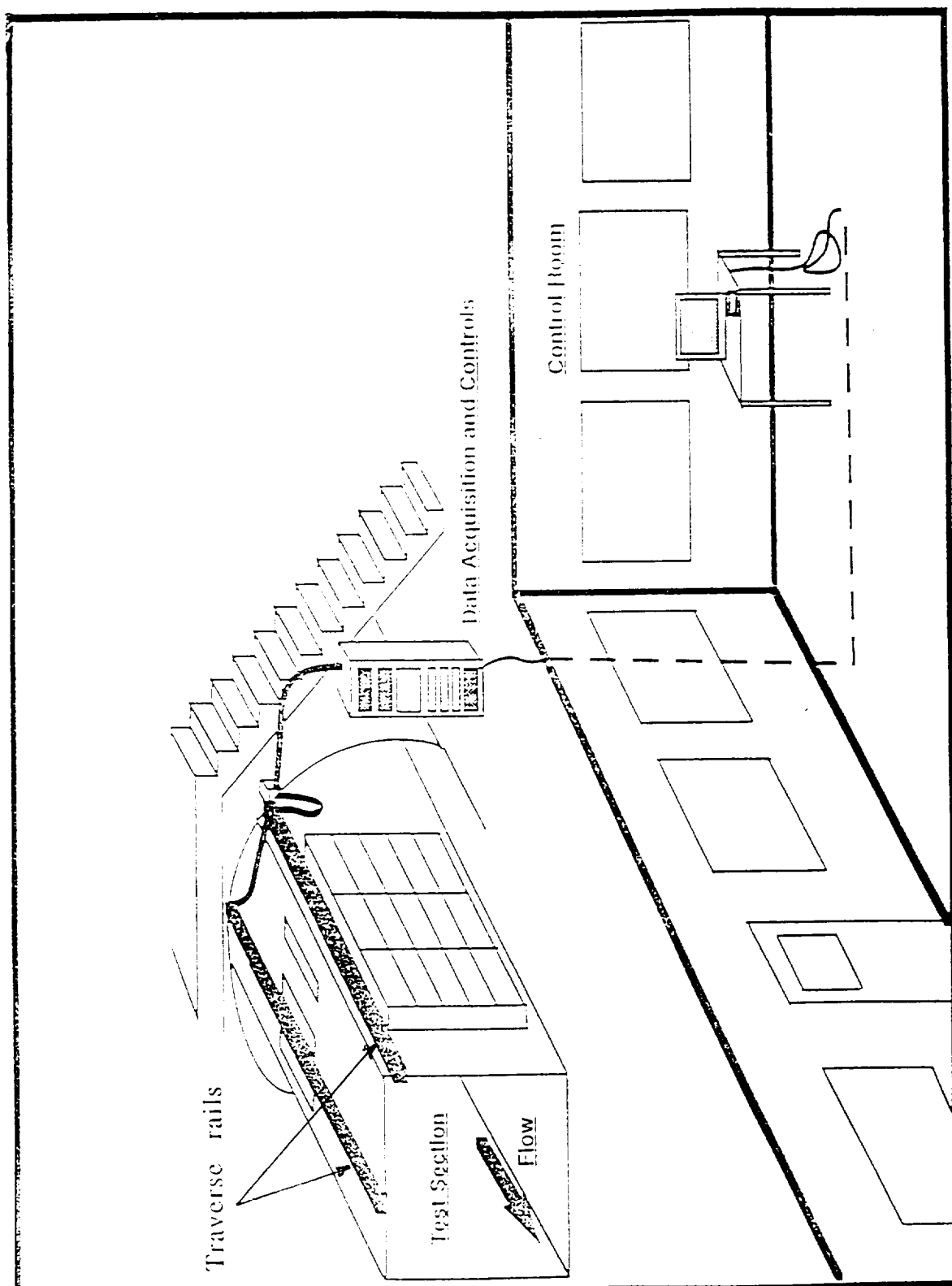


Figure 1c. Location of traverse system in the 11x11 Foot test section.

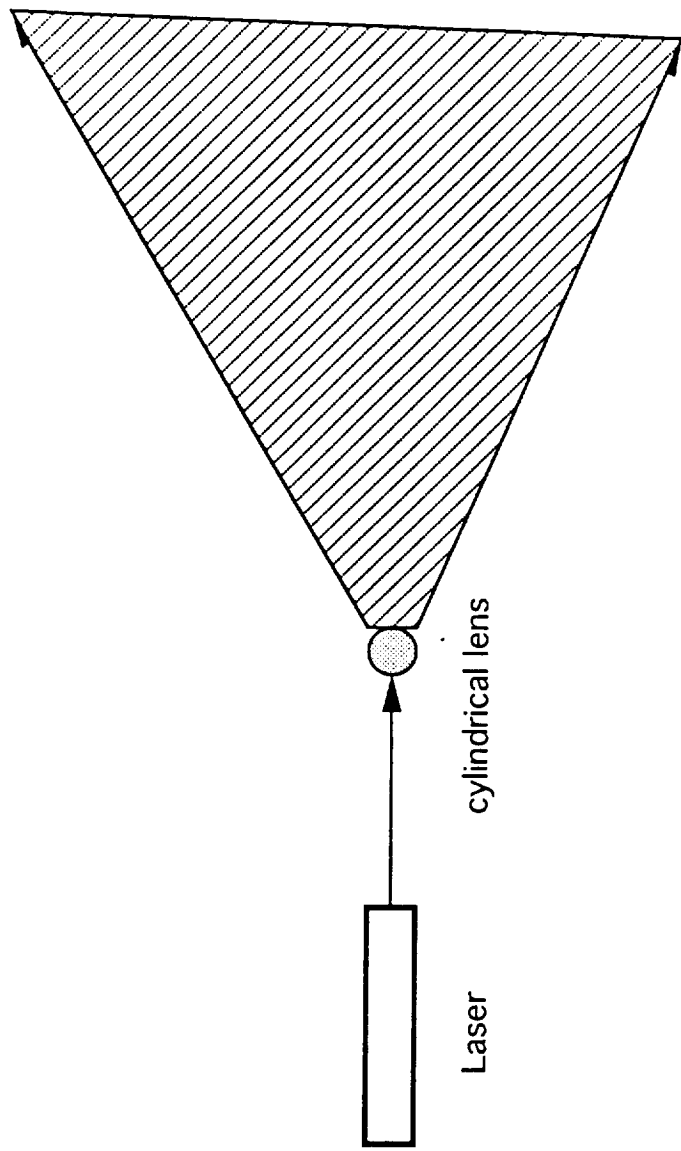


Figure 2a. Laser light sheet with a cylindrical lens.

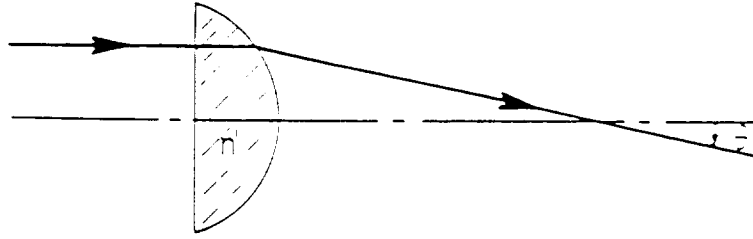


Figure 2b. Laser light sheet with a plane cylindrical lens.

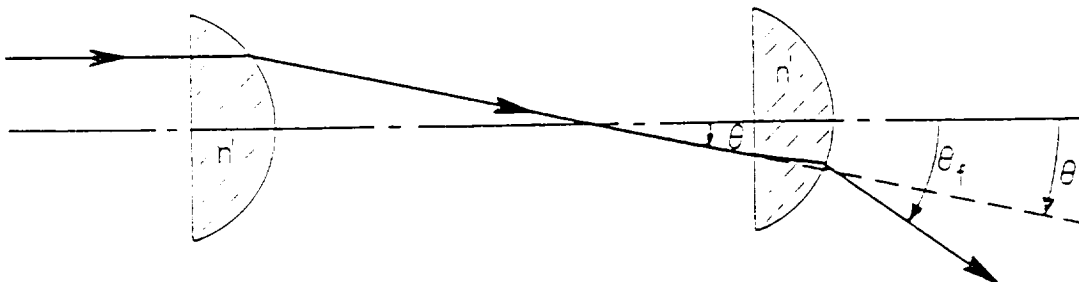
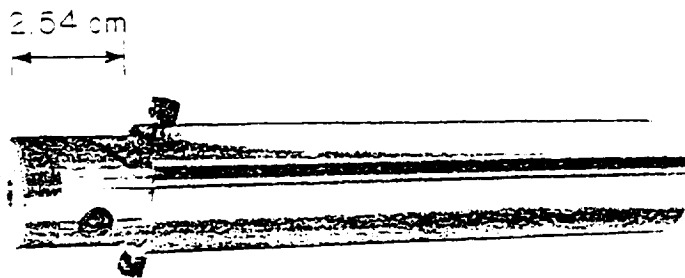


Figure 2c. Laser light sheet with telescope fanning. (after Snow and Morris)

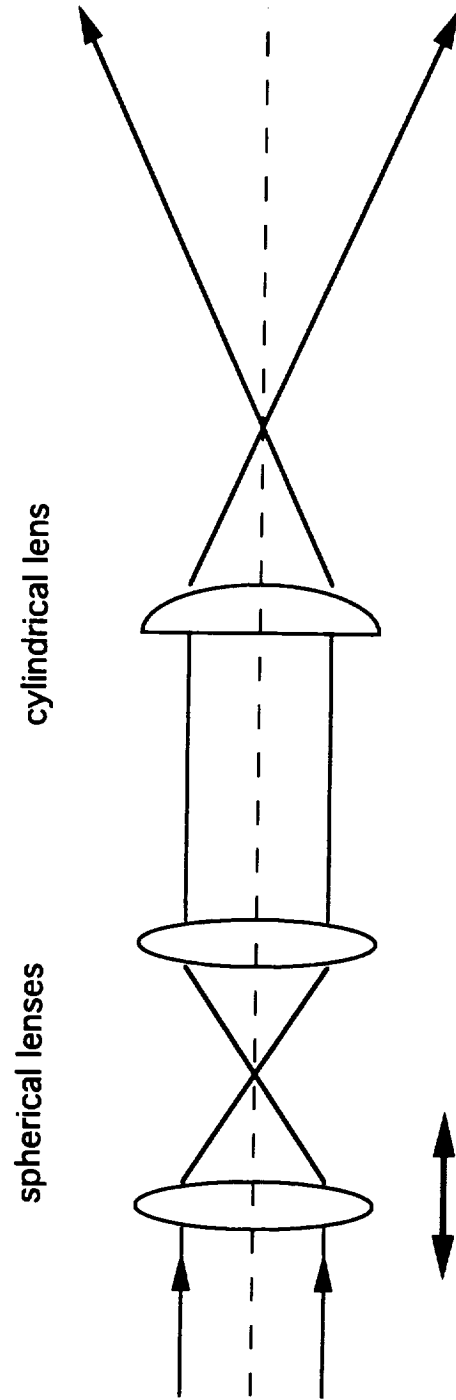


Figure 2d. Laser light sheet with variable fanning. (after Hentschel and Stoffegen)

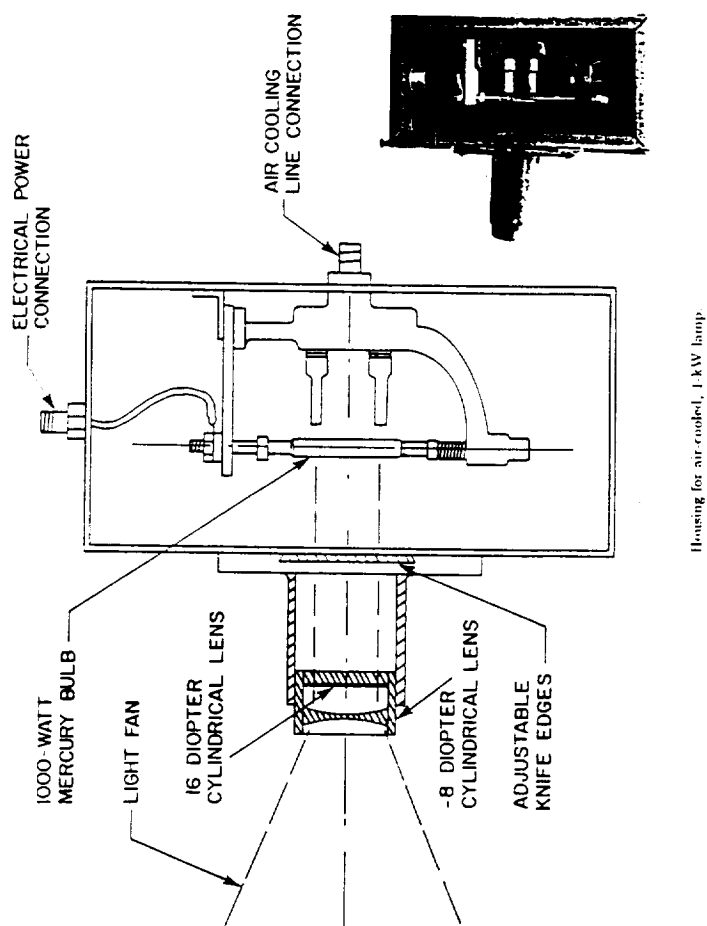
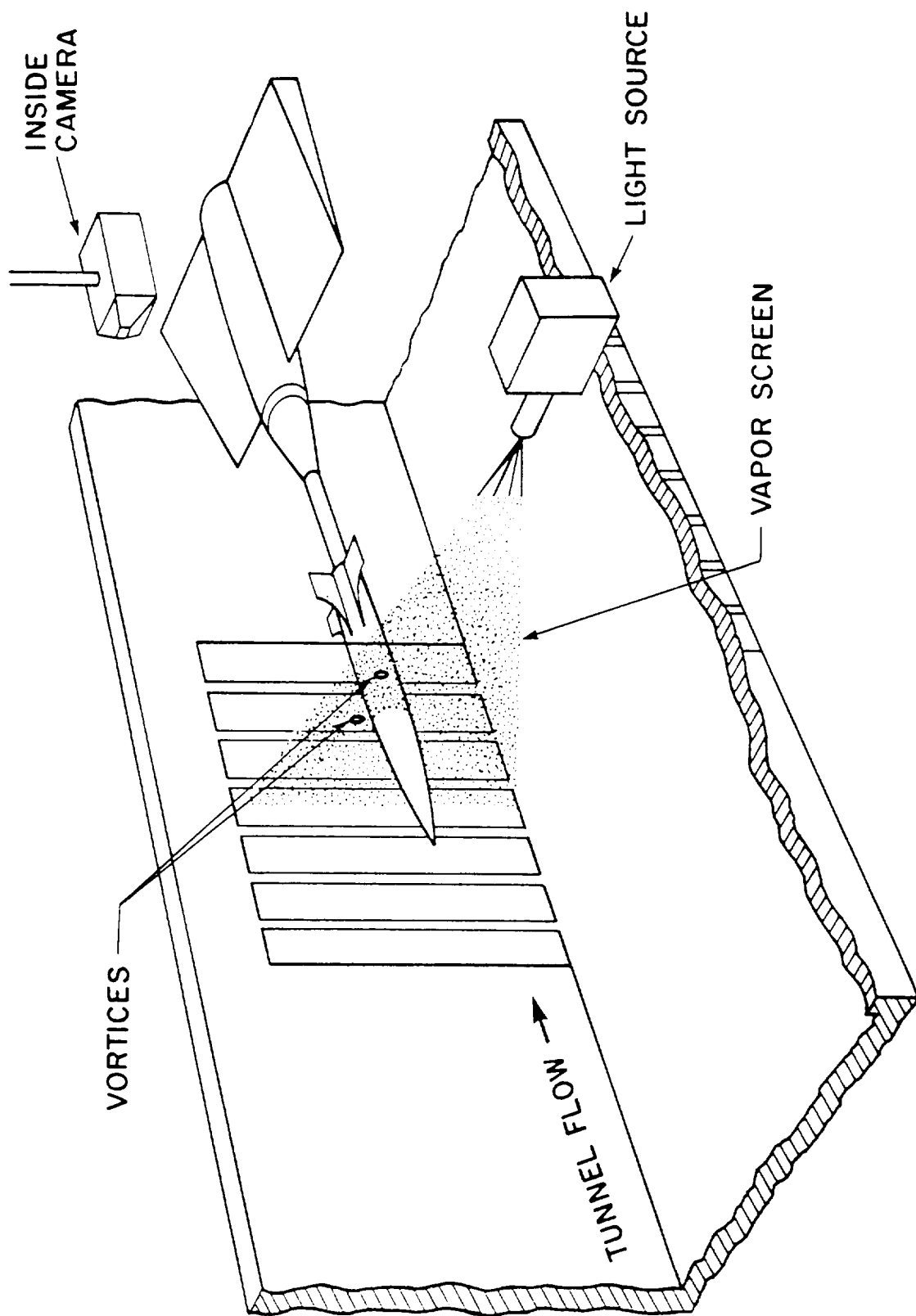


Figure 3. Light sheet generator with arc-lamps. (after Snow and Morris)



Perspective view to show concept.

Figure 4. Light sheet projection and recording set-up. (after Langley Unitary Plan Wind Tunnel)

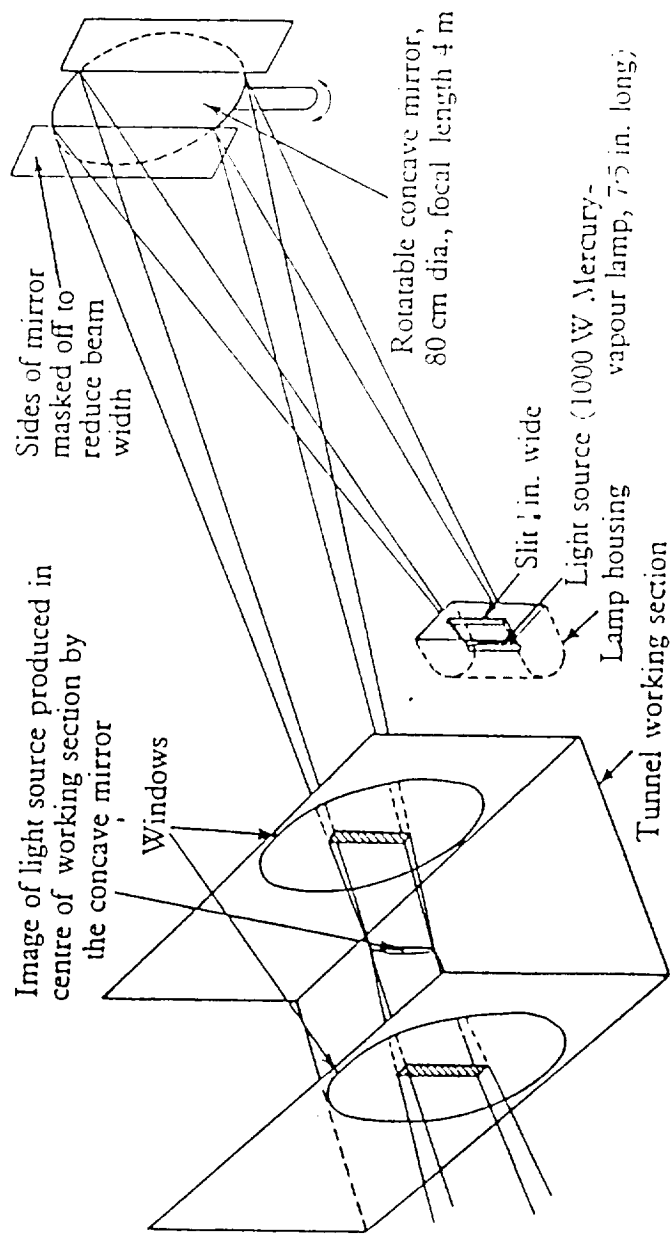
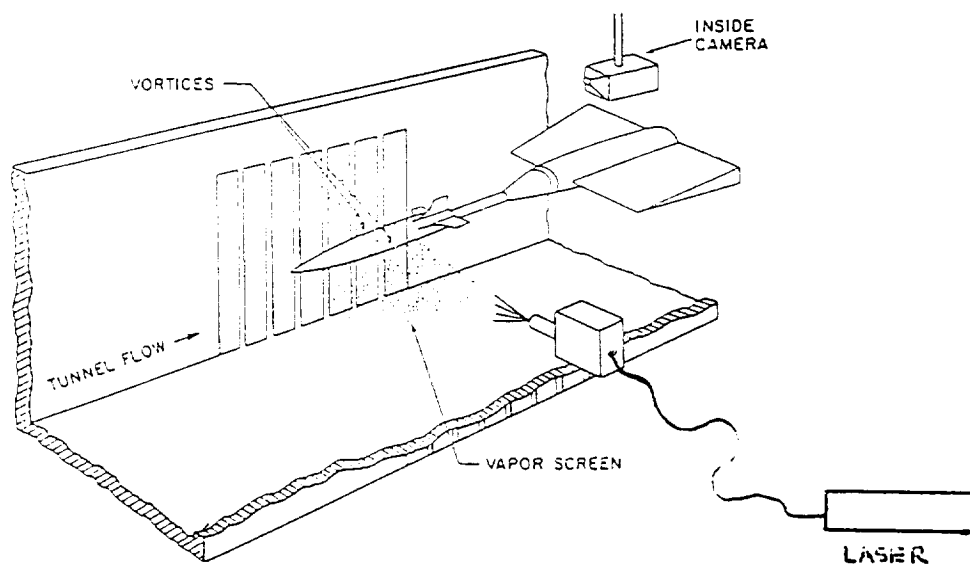
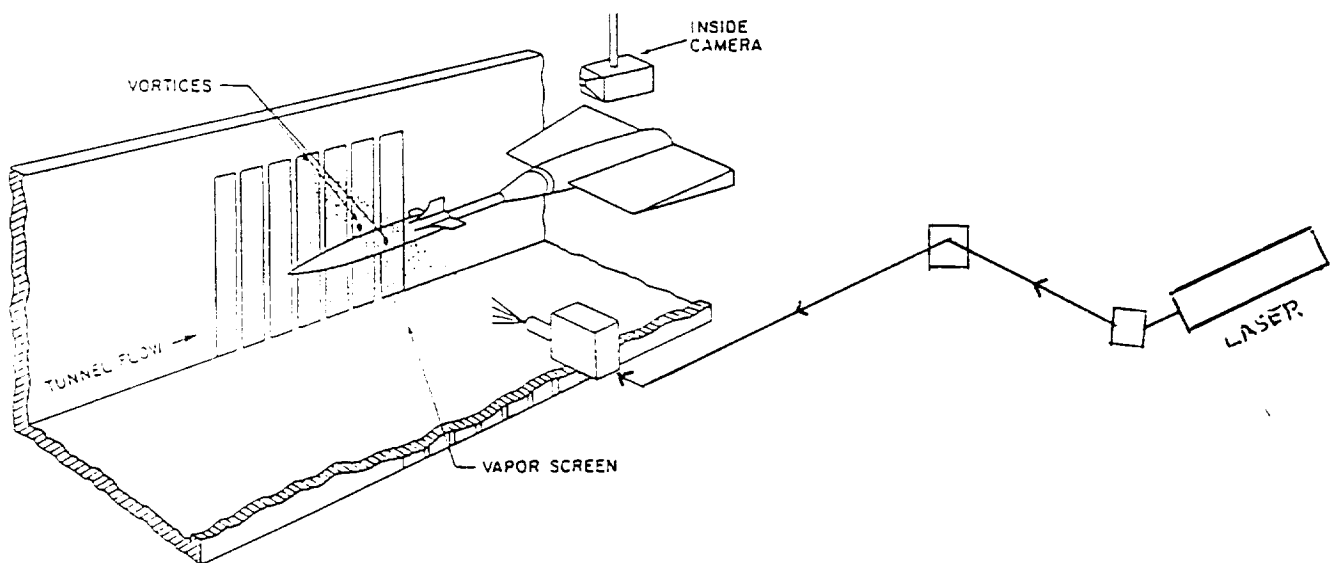


Figure 5. Light sheet generation with arc-lamp and schlieren optics. (after McGregor)



a. fiber optics transmission



b. mirror transmission

Figure 6. Light sheet generation with remote laser.

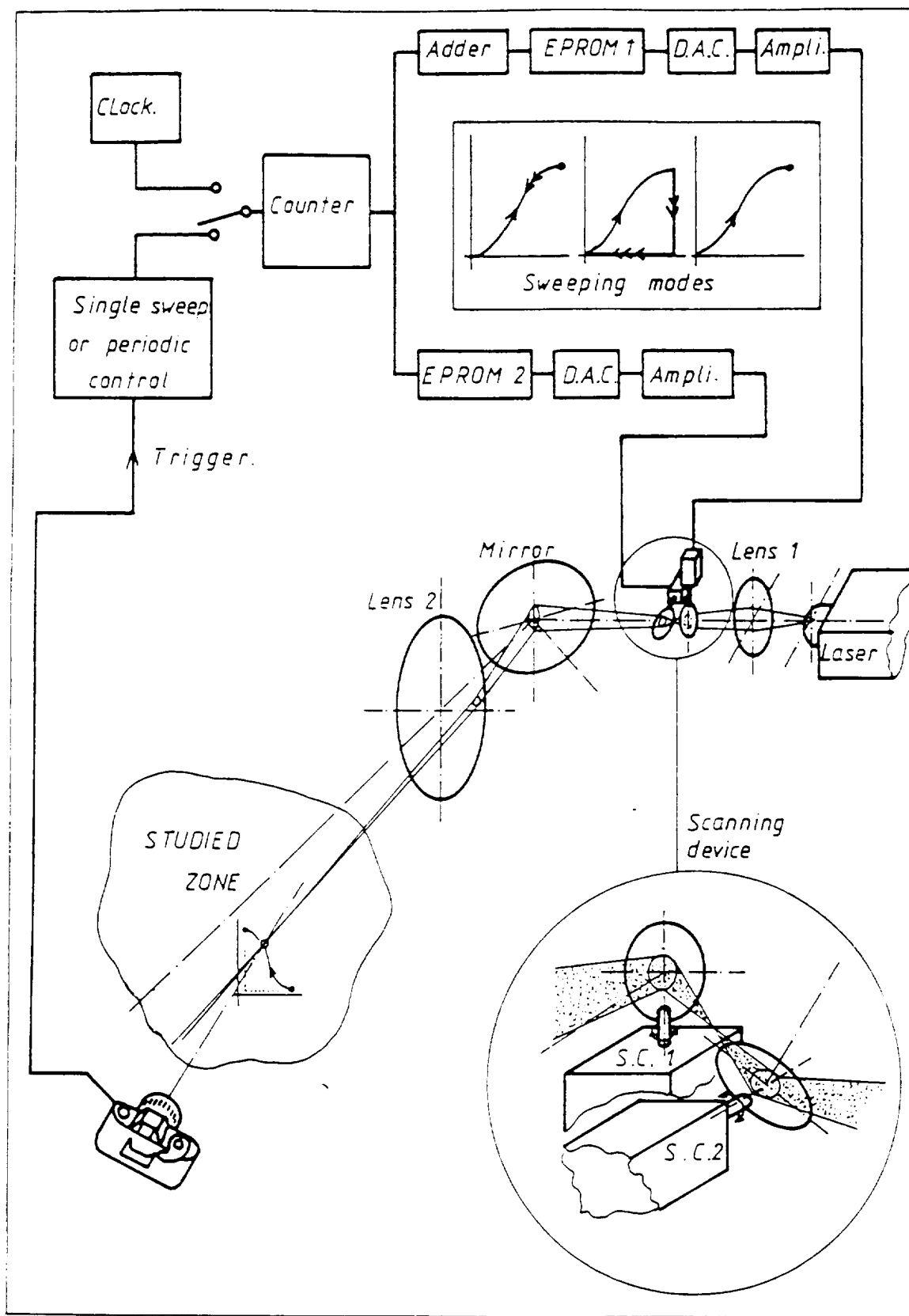


Figure 7. Light sheet generation by beam sweeping. (after Prenel, Porcar, and Diemunsch)

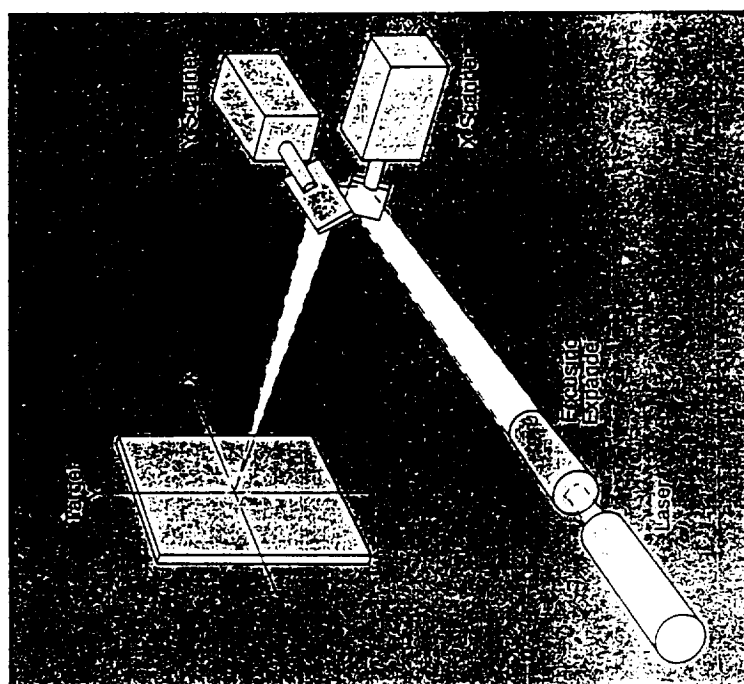
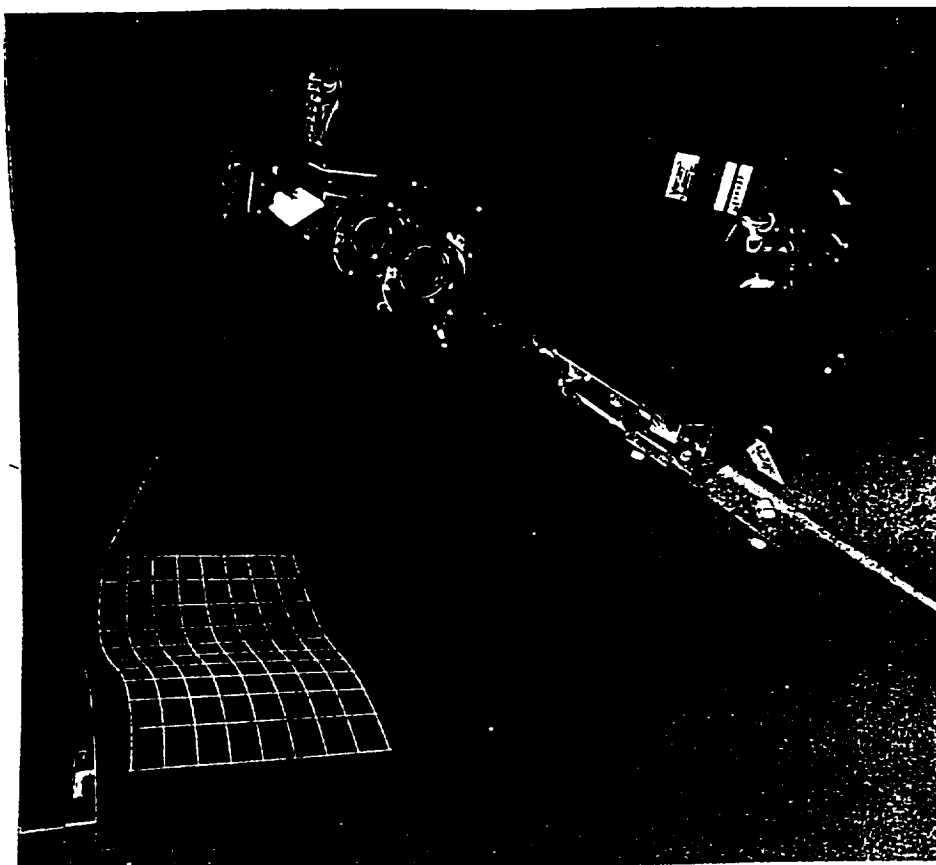


Figure 8. General Scanning Inc. beam sweeping system.

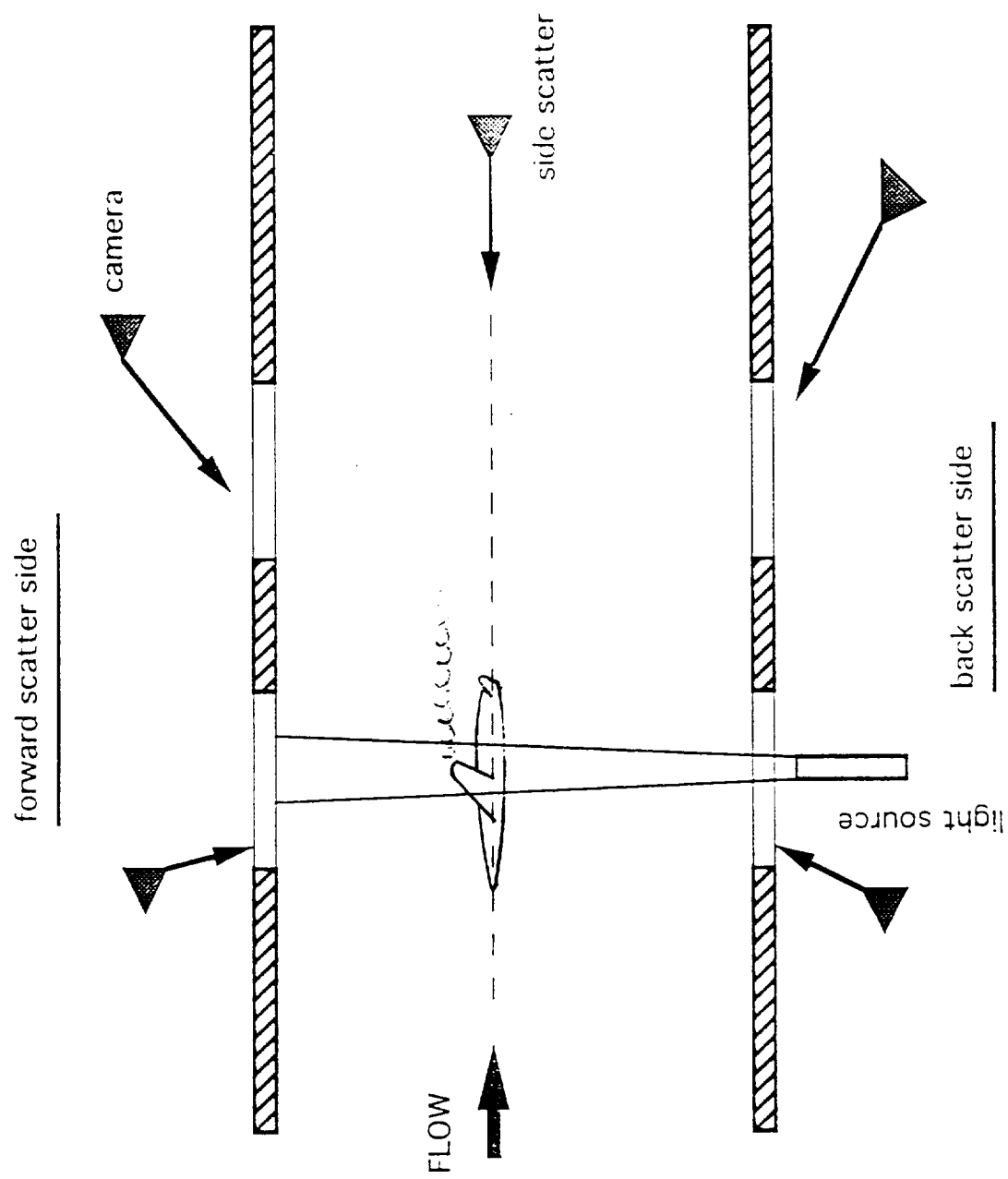


Figure 9. Typical camera positions for 9x7 Supersonic Wind Tunnel.

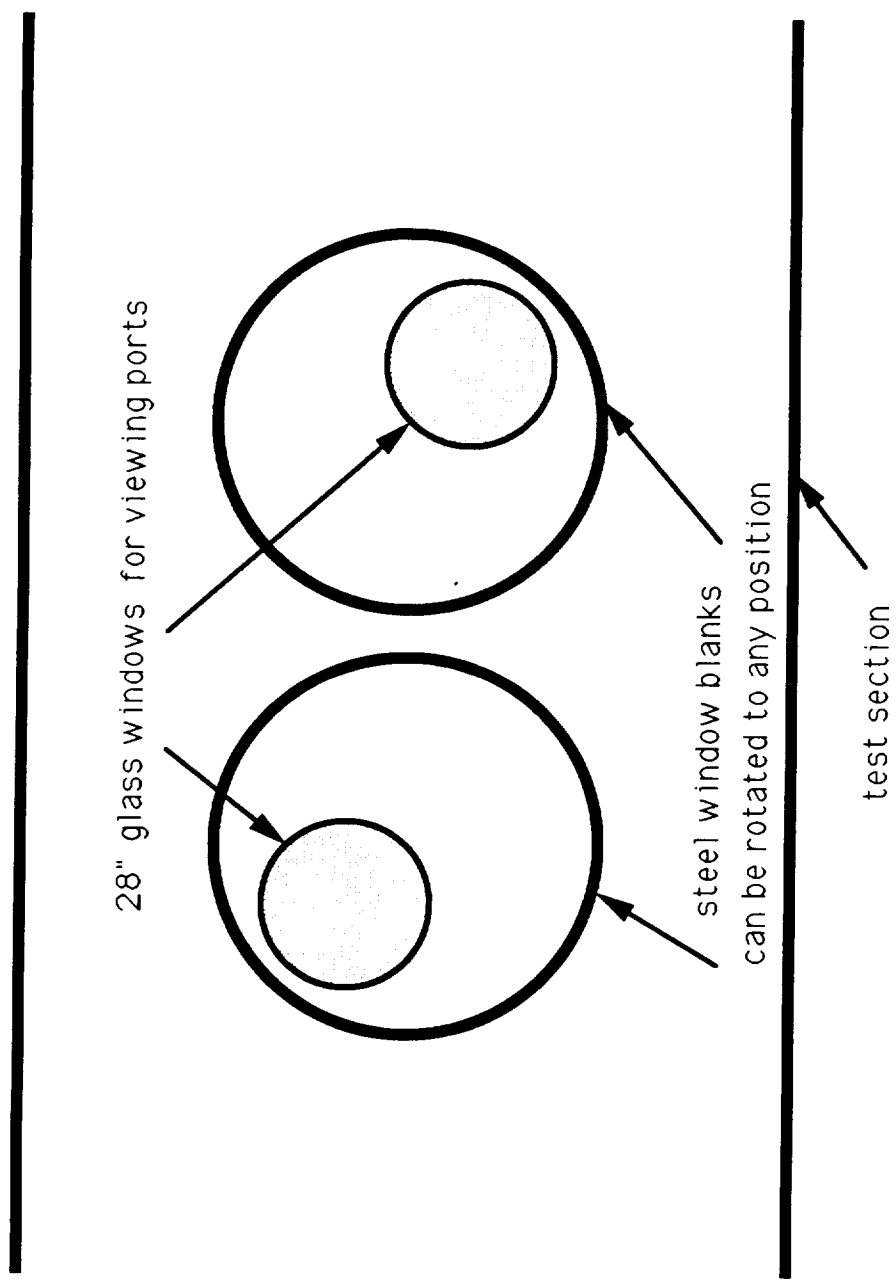


Figure 10. Viewing port arrangement of 9x7 Foot Supersonic Wind Tunnel.